ARCHITECTURAL SYSTEM USING A RETRACTABLE STRUT ALIGNED IN A BASE PLANE AND AN EXTENSION STRUT PROTRUDING ACUTELY FROM THE BASE PLANE

Field of the Invention

This application relates generally to architectural systems and more particularly to node and strut configurations.

Background of the Invention

Despite the many advances in materials over the past several decades, and the continuing interest in alternative building styles such as dome structures, the use of spaceframes in construction continues to be rather limited. Although node and strut systems have been devised and used by some, only very limited types of geometries, generally those based on the cube or pyramid, have achieved widespread use.

One noteworthy exception is the pioneering work of Steve Baer, who on 27 Mar. 1973 was issued U.S. Patent 3,722,153 ("Structural System"). The Baer patent teaches rigid, lightweight systems of nodes and struts, but does not provide any mechanism for ensuring rigid engagement between nodes and struts in a complex spaceframe. The teaching in the Baer patent is likewise limited by the small number of varieties of base triangles included.

Further, useful advances were taught in U.S. Patent 5,265,395 ("Node Shapes of Prismatic Symmetry for a Spaceframe Building System") issued 30 Nov. 1993 to Haresh Lalvani. The Lalvani patent teaches nodes and struts of various geometries, but does not teach any system for using struts to rigidly couple adjacent layers. A similar design, simpler than Lalvani's but also lacking inter-layer triangulation, is shown in **Fig. 5** below.

Those skilled in the art have overlooked substantial benefits that might be achieved in economies of mass production, versatility, high rigidity, low weight and/or ease of assembly in architectural systems incorporating golden geometry. It is to these opportunities that the present invention is directed.

Summary of the Invention

The present invention is an architectural system that, in its most basic form, includes a triangular base which engages an extension . The base includes three "complete" struts (defined in the detailed description below) substantially aligned along three respective axes. These axes each intersect each other to form a triangle defining in a base plane. The triangle's vertices each correspond to a respective nucleus (described below) of nodes called A, B and C. This forms three base angles (called CAB, ABC, and CBA). Angle CAB has a positive value about equal to [j×20.9° + k×31.7° + m×36° + n×37.4°], where j, k, m and n are each an integer less than three. Angle ABC also has a positive value about equal to [q×20.9° + r×31.7° + s×36° + t×37.4°], where q, r, s and t are each an integer less than three. Subject to certain geometric restraints such as the necessity for the interior angles of a triangle to total 180°, these eight coefficient values can vary somewhat independently.

At least one of the base triangle struts comprises at least two rigid pieces able to move apart so as to produce a strut elongation. In a complex spaceframe where each node has a position constrained by struts already engaging it, each new strut installed should desirably have such a length correction mechanism so as to permit positive (areal) engagement with its nodes.

The extension comprises (at least) a fourth complete strut substantially aligned along a fourth axis that is neither coplanar with nor orthogonal to the base plane. The fourth axis, in fact, forms a substantially acute angle > 3° with the base plane. (Although additional extension struts may be orthogonal, adequate structural triangulation might not be achieved without at least one such acute angle.)

These and various other features as well as additional advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of the Drawings

Fig. 1 shows a basic architectural system of the present invention comprising a triangular base and an extension protruding therefrom.

Fig. 2 is a chart summarizing which figures in this description illustrate which integer values as used in the formulas described in the summary.

Fig. 3 shows a simple, trilaterally symmetric architectural system of the present invention, suitable for use in a table.

Fig. 4 shows an enlarged view of the respective positions of the nuclei of some of the nodes of **Fig. 3**.

Fig. 5 shows a simple but sub-optimal architectural system suitable for use in a chair.

Fig. 6 shows a top view of a pentagonal wall frame suitable for use as a floor, buttressed with a compact series of triangular supports each of the present invention.

Fig. 7 shows a pyramid-like structure suitable for use as a building of three or more stories, requiring only three or four lengths of struts.

Fig. 8 shows the axes and nuclei of all of the front-most nodes of the structure of **Fig. 7.**

Fig. 9 shows a spaceframe structure of the present invention that would be suitable for a swimming pool.

Fig. 10 shows the axes and nuclei that correspond with struts and nodes of the rear right quarter of **Fig. 9.**

Fig. 11 shows an architectural system useful for constructing a lightweight, very rigid tower.

Fig. 12 shows a node and strut configuration suitable for use with some embodiments of the present invention at a 1:1 scale.

Fig. 13 shows a magnified cross section of the bolt and node of **Fig. 12,** fully engaged with one another.

Fig. 14 shows three nodes each formed by a different type of slice across a node like that of **Fig. 12.**

Fig. 15 shows a more complex and versatile polyhedral node which can be used for any of the nodes of any of the structures shown in **Figs. 3-11.**

Fig. 16 shows another modular "shell-type" node suitable for use as any of several of the nodes in structures shown in **Figs. 7&11.**

Fig. 17 shows several straps like those of **Fig. 16,** drawn to scale in various positions.

Fig. 18 shows the construction of another style of composite node.

Fig. 19 shows how a gap between two of the components of the composite node of **Fig. 18** permit a tongue of a strut to be inserted therebetween.

Detailed Description

Although the examples below show more than enough detail to allow those skilled in the art to practice the present invention, subject matter regarded as the invention is broader than any single example below. The scope of the present invention is distinctly defined, however, in the claims at the end of this document.

Numerous aspects of spaceframe architecture that are not a part of the present invention (or are well known in the art) are omitted for brevity, avoiding needless distractions from the essence of the present invention. For example, this document does not include much detail about material selection or node design, except where the inventor has observed opportunities for a synergy.

Definitions and clarifications of certain terms are provided in conjunction with the descriptions below, all consistent with common usage in the art but some described with greater specificity. As used herein, an "axis" of a strut refers to a line segment very closely aligned with the strut. An axis has a "length," ordinarily greater than that of the corresponding strut, bounded by nuclei of two nodes with which the strut engages. As used herein, a "nucleus" of a node is a point (usually within the node) aligned with the axes of struts that engage with the node. For nodes that

are not substantially round, a nucleus will be approximately equidistant from two or more node surfaces that each engage a strut. As used herein, a "radius" of a node refers to a distance measured from a nucleus to a farthest surface from the nucleus. Thus, the term is defined even for nodes of irregular shape. Two angles are "substantially equal" herein if they are within half a degree. Other quantities are "substantially equal" if they are within 0.5% of each other.

A "complete" strut is one that substantially surrounds its corresponding axis for the entire length between the nodes engaged by the strut. Such a strut will distribute an axial tension or compression on opposing sides of the axis. An arcuate or other "incomplete" strut, by contrast, will bow further away from the axis under axial compression. This greatly reduces the rigidity of the system, or necessitates a needless increase in strut weight.

Turning now to **Fig. 1,** there is shown a basic architectural system **100** of the present invention. A triangular base **101** comprises three nodes **110,130,150** and three complete struts **120,140,160**. Strut **120** engages nodes **110,130** and is substantially aligned along axis **129**. Strut **140** engages nodes **130,150** and is substantially aligned along axis **149**. Strut **160** engages nodes **110,150** and is substantially aligned along axis **169**. Base plane **199** contains the three axes **129,149,169** and their endpoints **119,139,159**. An extension **102** comprises at least one complete strut **170** extending from the triangular base non-orthogonally (i.e. substantially aligned along an axis **179** forming a substantially acute angle **198** with base plane **199**).

Fig. 2 is a chart summarizing which figures in this description illustrate which integer values as used in the formulas described in the summary above. Column **288,** for example, indicates that a triangular base of **Fig. 5** corresponds with j=r=2 and n=1. Using the formula, one expects a first interior angle of 79.2 degrees, which is in fact formed between the axes of struts **525,527**. One similarly expects a second interior angle of 63.4 degrees, which is formed between the axes of struts **527,528**. The third interior angle is less than 60 degrees, also. One of ordinary skill will readily be able to apply the formula and identify the triangular base(s) corresponding to any of the columns in **Fig. 2**, as it is shown in subsequent figures. **Fig. 2** illustrates that a wide variety of triangular bases suitable for use in the present invention are illustrated in these figures.

Fig. 3 shows a simple, trilaterally symmetric architectural system **300** of the present invention, suitable for use in a table. Three inner nodes **310** and six outer nodes **320,330** are positioned at the surface of the table. Identical tabletop struts **311,321,331** couple each inner node **310** to two outer nodes **320,330** in an equilateral triangle. The equilateral triangles are coupled to one another by longer struts **312,313** as shown. The nodes **310,320,330** of each equilateral triangle are each coupled to a knee-height node **340** by a respective upper support strut **314,324,334**. Floor nodes **350** are each coupled to a respective inner node **310** by a vertical strut **315**. Floor nodes **350** are also each coupled to a respective knee-height node **340** by a lower support strut **317**. The 37.4° angle indicated in the left-most data column of **Fig. 2** is between axes **459,479**. The 101° angle between axes **449,479** corresponds with r=2 and t=1. The extension comprises, for example, the strut substantially aligned with axis **448**. **Figs. 3&4** thus embody the present invention, as do **Figs. 6-11**.

Fig. 4 shows an enlarged view **400** of the respective positions of the nuclei **410,420,430,440** of some of the nodes **310,320,330,340** of **Fig. 3**. Each dotted line represents an axis along which a respective strut is aligned. For example, each lower support strut is aligned along a respective axis **379**. Each vertical strut **315** is aligned along a respective axis **459**. Each inner node support strut **314** is aligned along a respective axis **449**. Axes **449,459,479** form a triangle defining the (vertical) base plane. Axes **449,459** form an interior angle of the base triangle about equal to 2x20.9° (j=2,k=m=n=0). Axes **449,479** form an interior angle about equal to 2x31.7° + 37.4° (r=2,t=1,q=s=0). The third interior angle is less than 60°. Outer node support struts **334** are each aligned along a respective axis **448** that forms a substantially acute angle with the base plane.

It will be appreciated by those skilled in the art that the structure of **Figs. 3&4** provides a higher degree of rigidity than comparable structures of the prior art, for a given choice of material. Moreover, the structure is built with only six lengths of struts.

Fig. 5 shows a simple, bilaterally symmetric architectural system **500** suitable for use in a chair. Nodes **510,520** are at two corners of a square formed by struts **501,511,521,531**. Nodes **520,530** are likewise at two corners of a rectangular seat frame formed by struts **514,524,531,541**.

The seat side struts **514,524** are shorter than the back side struts **511,521** so that node **520** is offset from node **530** by about 13.4% less than it is offset from node **510**.

Struts **524** and **528** are aligned along respective axes that form a 37.4° angle. Struts **524** and **561** are aligned along respective axes that form an angle about equal to 20.9°+20.9°+31.7°+37.4°. Thus it would appear that struts **524,528,561** (with nodes **520,530,540**) would form a suitable base triangle of the present invention, in a vertical plane. Unfortunately, this design has a noteworthy weakness: All of the direct extensions from this base triangle extend either along within the same plane (i.e. struts **525,527** to node **550**) or perpendicular to the plane (i.e. "aligned substantially parallel to" strut **531**). Applicant has determined that such designs are often not adequately rigid to resist a shear force parallel to the base plane. Such designs can therefore be susceptible to vibration, deformation and degradation that can have severe consequences in larger scale applications.

Fig. 6 shows a top view of a pentagonal wall frame **600** suitable for use as a floor, buttressed with a compact series of triangular supports each of the present invention. The frame **600** includes five outer nodes **610,640** and five inner nodes **630,660** that all lie in a primary plane. Five intermediate nodes **620,650** all lie in a secondary plane (behind the primary plane, as shown).

Struts **612,614,624** are substantially aligned along respective axes that form an isosceles triangle with two interior angles of about 20.9° and one of about 140.2°. (Note that this is equal to 31.7°+31.7°+37.4°+37.4°.) A triangular base of the same size and shape is formed by strut **624** with struts **622,634**.

Struts **631,632,642** are substantially aligned along respective axes that form an isosceles triangle with two interior angles of about 72° and one of about 36°. (Note that this corresponds to a triangle with m=s=2 and j=k=n=q=r=t=0, in terms to the formula given in the summary.) A larger base triangle forming these same angle is formed with corners in nodes **610,640,670**. Note that the longer sides of this base triangle are very long in comparison to their thickness. Rigidity is maintained, however, because each is a "supported strut," one that includes a radially protruding extension (such as strut **631**) generally supporting the mid-section of the supported strut. Finally, another advantage of frame **600** is the small variety of struts required to build it. As shown, only four lengths of (unsupported) struts are used.

Fig. 7 shows a pyramid-like structure **700** suitable for use as a building of three or more stories. (For clarity, nodes and struts in **Fig. 7** are shown with a larger-than-typical diameter, relative to their lengths.) As shown, structure **700** can be built with only three lengths of struts.

Three of the nodes of pentagonal wall frame **600** are re-used in **Fig. 7**. This illustrates that frame **600** can be used as an especially rigid and compact floor in structure **700**. In this case, the intermediate nodes **620,650** form a horizontal pentagon of the same size and orientation as that of node **780**. Also, building structure **700** to incorporate frame **600** requires a total of only four lengths of struts.

Fig. 8 shows the axes and nuclei of all of the front-most nodes of structure **700**. Interior and posterior nodes and struts (shown in **Fig. 7**) are omitted for simplicity and to resemble how structure **700** would appear when covered by conventional walls. Nuclei **810,840,870,880** correspond respectively to nodes **610,640,670,780** of **Fig. 7**.

Fig. 9 shows a spaceframe structure **900** of the present invention that would be suitable for a swimming pool. The rear half **901** is symmetric with the front half, and the right half **902** is symmetrical with the left. Only five lengths of struts are required for constructing this spaceframe, as shall be illustrated with respect to **Fig. 10**.

Fig. 10 shows the axes and nuclei that correspond with struts and nodes of the rear right quarter of **Fig. 9**. The axes **1017,1027,1037,1047,1057,1067,1077** are all of the same length L. These axes are respectively aligned with seven of the 20 shortest struts shown in **Fig. 9**. These 20 struts have substantially the same length (i.e. to within typical manufacturing tolerances) as one another. The 20 struts are shorter than L so as to allow each node to which the strut affixes to occupy the respective nucleus.

Axes **1031,1041,1051,1061,1071,1081** are each longer than L by about 5.14%. Each is substantially aligned with a strut about as long as L shown in structure **900,** of which there are 16. Similarly there are five struts in structure **900** having a maximum length, each aligned along a respective axis such as axes **1042,1052,1082**. Structure **900** also contains 16 basically identical struts somewhat shorter than those of maximum length, aligned along axes like

1018,1048,1058,1078,1088. And finally, structure **900** contains eight basically identical, medium-length struts aligned along axes like **1045,1085**.

Struts or axes having the same last digit, within **Fig. 10**, have substantially the same length as one another. The same holds true within any given one figure elsewhere in this document. In fact, the relative proportions between axis lengths can be derived from the angles given, in a triangle, or vice versa. Moreover the axis lengths are to scale (typically oblique) for all of the figures in this document. For these reasons it suffices to give angles or lengths to enable the construction of further frames shown in this document.

Fig. 11 shows an architectural system **1100** useful for constructing a lightweight, very rigid tower. Nucleus **1110** is the highest point, stellated from a pentagonal base comprising nuclei **1120,1130,1140,1150**. **Fig. 11** shows all of the angles of the surface of the "wedge" bounded by nuclei **1110,1130,1140,1170,1180** are shown explicitly. This wedge is used a total of five times about the highest nucleus **1110**.

The base of the system **1100** is a pentagon having five sides (including axis **1112**) and five points (including nuclei **1170,1180**). A base triangle of the present invention includes axes **1112,1117,1127** and nuclei **1170,1180** and angles as shown within that triangle.

One surface axis, the one just below axis **1137,** is not shown so as to reveal the position of a horizontal axis **1132** the same length as that of base axis **1112**. This horizontal axis **1132** is part of two base triangles of the present invention, with angles as shown. The complete structure includes a total of twenty horizontal axes like **1112,1132**. Twenty substantially identical struts (not shown) aligned along these axes provide four pentagonal floors within structure **1100**. If desired, each of these simple floors can be augmented by using a vertically compact pentagonal frame like frame **600** of **Fig. 6**.

Fig. 12 shows a node **1210** and strut **1290** configuration suitable for use with some embodiments of the present invention at a 1:1 scale. Strut **1290** comprises a solid rectangular plank of a hardwood **1289,** a steel strap, and a threaded bolt **1299**. The steel strap comprises a left portion **1291,** a right portion **1292,** and an engagement portion **1293**.

Node **1210** is an aluminum polyhedron having a threaded hole **1211** in each exterior side. When bolt **1299** engages node **1210** as indicated, the angled portions of the sides **1291,1292** yield slightly to permit a solid engagement between the engagement portion **1293** of the strap and the top surface of the node **1210** even if the strut **1290** is slightly too long or short. Even while providing this flexibility, strap is wide, thick, and short enough as shown to make the overall node/strut joint highly rigid so long as the disengaged strap position (i.e., the position along axis **1297** at which the strut has axial stresses of 1 Newton or less) is within about R/50 of node **1210,** where R is the radius **1298** of node **1210**.

The closest successive holes **1211** of node **1210** are 36 degrees apart (although some sides **1212** lack engagement holes so as to simplify node manufacture). Node **1210** is therefore also capable of supporting rigid angles of 72 degrees and **108** degrees, the same ones required for structure **700** (of **Fig. 7**). A problem may exist, however, that would require a modification of the node **1210** or strut **1290** to enable the construction of structure **700**. **Fig. 12** shows a node radius **1298** that is less than half of the maximum strut diameter **1288**. For this reason, it may be impossible to have several struts engage with node **1210** simultaneously in a desired configuration. For example, it may be desirable to replace node **1298** with one having a radius that is 50% larger than that shown (but without enlarging the engagement holes **1211**).

Fig. 13 shows a magnified cross section of bolt **1299** fully engaged with node **1210,** holding engagement portion **1293** solidly against an outer surface of node **1210**. A preferred mechanism for doing this is the use of a strut having several load surfaces **1215,1216** protruding (radially) from the axis **1297**. The load surfaces **1215,1216** are configured to permit axial force transfer from access surfaces **1295,1296** of the strut **1290**. A threaded configuration like this can easily be made to resist relative movement between the node **1210** and strut **1290** under axial compression or tension in excess of 100 Newtons or more.

More sophisticated engagement mechanisms are available. For example, U.S. Patent 4,193,706 ("Bolt Connections Between Tubular Rods and Junctions in Three-Dimensional Frameworks") issued 18 Mar. **1980** to Eberlein et al. teaches one such system. Similar systems are

available for purchase from Mero Structures, Inc. in Menomonee Falls, Wisconsin (262-255-5561, www.mero.com).

Fig. 14 shows three nodes **1410,1420,1430** each formed by a different type of slice across a node like **1210** (of **Fig. 12**). These would be suitable for use in some of the positions of structure **700** (of **Fig. 7**). When used as outer corner nodes, a flat side of one of these could be used so that the node would protrude less from the structure. This would also reduce the weight of the structure with a fairly small loss of rigidity.

Fig. 15 shows a more complex and versatile polyhedral node **1510** which can be used for any of the nodes of any of the structures shown in **Figs. 3-11.** A half of this node **1520** is also shown, revealing its inner structure. Note that the interior **1525** is formed merely by boring a hole into the center of each side, the result being a large, multi-lobed cavity that compromises very little of the rigidity of the original solid polyhedron.

Fig. 16 shows a "shell-type" node **1600** suitable for use as any of several of the nodes in structures shown in **Figs. 7&11.** Several straps **1610** make up the shell, preferably made of steel. The ends of five straps converge to form a roughly circular hole **1611** which can be used for securing a strut. The strut can be a bolt and nut configured to secure the five straps **1610,** but more preferably the straps are welded or adhesed to one another and to the strut. In the mid-section of each strap **1610** is a slot **1612**. The slot of each strap provides a very broad range of angular positions any of which can be used to secure a cylindrical strut by conventional means. For the entire structure of **Fig. 11**, all of the necessary angles can be achieved with struts positioned at end-holes (like **1611**) and at the center of slots (like **1612**). Because **Fig. 16** is shown to scale, one of ordinary skill can easily determine what other angles between axes of struts are enabled using nodes of this design. **Fig. 17** shows several straps **1721,1722,1723,1724** identical to **1610** to scale, defining the components of node **1600** with greater clarity.

Fig. 18 shows the construction of another style of composite node **1800**. **Fig. 19** shows how a gap between two of the components **1911,1912** of the composite node **1800** permit a tongue **1993** of a strut **1990** to be inserted therebetween. Inter-strut angles as small as 36° are achievable with nodes identical to **1800**, which is all that is needed for a structure like that of **Fig. 7**. During

assembly, a bolt or other fastening mechanism squeezes the components **1912** together, completing the node and securing the tongue against axial (vertical) displacement relative to node **1800**. Once the tongue is moved into position, conventional wood screws (not shown) affix the Y-shaped member comprising the tongue **1993** to the rest of the strut **1989**.

Alternatively characterized, a first embodiment of the present invention includes a triangular base (such as **101**) which engages an extension (such as **102**). The base includes three complete struts substantially aligned along their respective axes. These axes each intersect each other to form a triangle contained in a base plane. The triangle's vertices each correspond to a respective nucleus of nodes called A, B and C. This forms three base angles (called CAB, ABC, and CBA). Angle CAB has a positive value about equal to $[j\times20.9° + k\times31.7° + m\times36° + n\times37.4°]$, where j, k, m and n are each an integer less than three. Angle ABC also has a positive value about equal to $[q\times20.9° + r\times31.7° + s\times36° + t\times37.4°]$, where q, r, s and t are each an integer less than three. Note that these angular constraints can impose size limitations on the nodes. For example, the third node (C) engages the second and third complete struts and must be large enough to maintain the third base angle BCA at a positive value less than 60°. Note also that these angular restraints permit a great variety of combinations. For example, j, n, q and t may all be even in a given base triangle.

At least one of the base triangle struts comprises two or more rigid pieces (such as **1289,1299**) able to move apart so as to produce a strut elongation. The extension comprises a fourth complete strut substantially aligned along a fourth axis forming a substantially acute angle with the base plane.

In a second embodiment, the fourth axis forms an angle with the first, second or third axis that is substantially equal to a reference angle. The reference angle is selected from a group consisting of 13.3°, 15.5°, 20.9°, 22.2°, 31.7°, 35.3°, 36°, 37.4°, 37.8°, 41.8°, 44.5°, 45°, 54.7°, 58.3°, 60°, 63.4°, 65.9°, 69.1°, 70.5°, 72°, 75.5°, 76.7°, 79.2°, 82.2°, 90°, 97.8°, 100.8°, 103.3°, 104.5°, 108°, 109.5°, 110.9°, 114.1°, 116.6°, 120°, 121.7°, 125.3°, 135°, 135.5°, 138.2°, 142.2°, 142.6°, 144°, 144.7°, 148.3°, 155.9°, 157.8°, 159.1°, 164.5°, and 166.7°. The extension (such as **102**) comprises a polygon (such as a triangle or quadrilateral, see **Fig. 9**) having N sides each

occupied by a respective complete strut. The third axis contains one of the N sides, and the fourth axis contains another of the N sides.

In a third embodiment, one of the struts (such as **170**) has a maximum diameter D (such as **1288**) and one of the nodes (such as **110**) has a radius R (such as **1298**) that is not less than D/2. The struts are each primarily composed of a non-metallic material (such as wood). Each of the base's nodes includes couplings engaging two of the struts of the base triangle. Each of the couplings is capable of retaining its strut in a fixed position relative to the node, even under a tension of at least 100 Newtons along the axis therebetween. This is optionally accomplished by providing load surfaces (such as **1215,1216**) on each node and access surfaces (such as **1295,1296**) on each strut. (These access surfaces are those configured to exert force each on a respective one of the load surfaces so as to resist an axial movement of the strut relative to the node.)

All of the structures and methods described above will be understood to one of ordinary skill in the art, and would enable the practice of the present invention without undue experimentation. It is to be understood that even though numerous characteristics and advantages of various embodiments of the present invention have been set forth in the foregoing description, together with details of the structure and function of various embodiments of the invention, this disclosure is illustrative only. Changes may be made in the details, especially in matters of structure and arrangement of parts within the principles of the present invention to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed. Although the preferred embodiments described herein are largely directed to conventional fasteners for node/strut couplings, it will be appreciated by those skilled in the art that many teachings of the present invention can be applied to other types of couplings without departing from the scope and spirit of the present invention.